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Vertical Wind Estimation
from Horizontal Wind Measurements.

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Vertical Wind Estimation From Horizontal Wind Measurements

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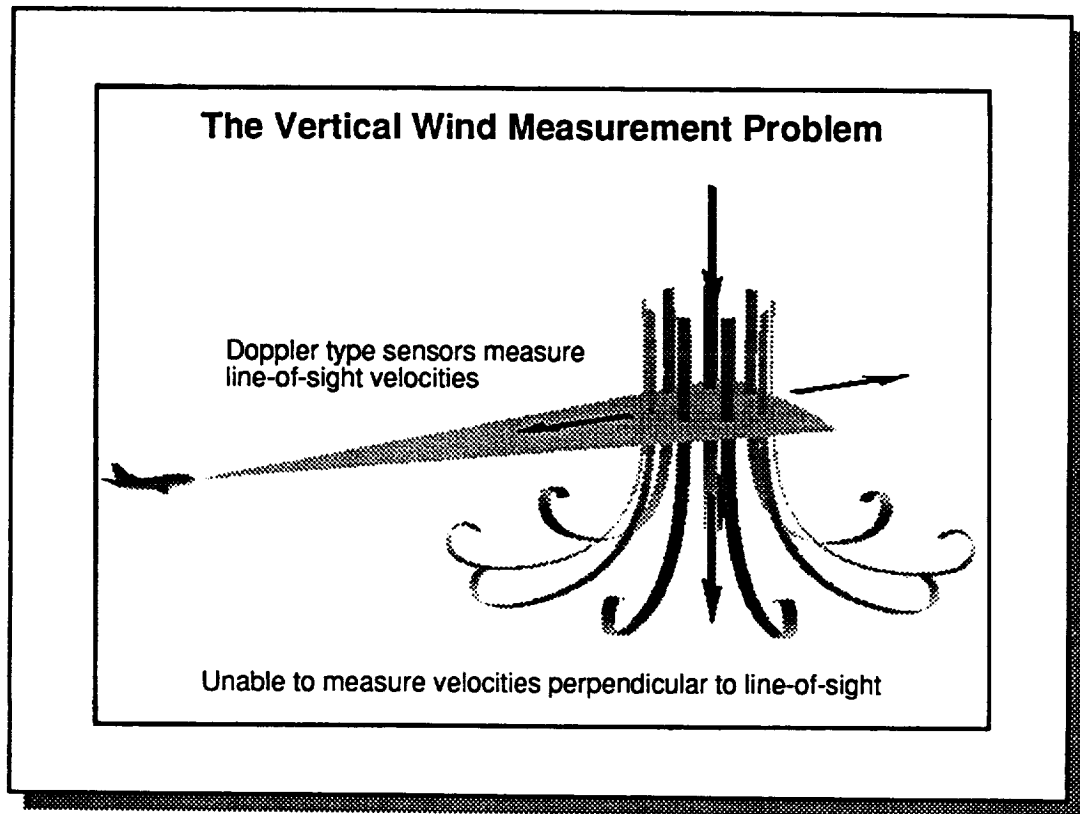
NASA/FAA Wind Shear Review Meeting

September 28-30, 1993

Outline

- The Vertical Wind Measurement Problem
- Vertical Wind Estimation Technique
- Simulation Study
- Flight Test
- Concluding Remarks

This presentation addresses an inherent problem with Doppler based forward-look wind shear detection sensors, which is their inability to measure wind velocities perpendicular to the sensor line-of-sight. The presentation will begin with a brief description of this limitation and how it effects hazard prediction. This will be followed by a description of a vertical wind estimation technique that is based on simple microburst models. The results of a radar simulation study and a series of flight tests evaluating this technique will then be presented. This will be followed by a summary and concluding remarks.



Two of the airborne forward-look sensor technologies being tested to provide advanced warning of wind shear are Doppler radar and LIDAR. Both measure the Doppler shift of reflected light or radio waves from the aerosols, rain drops and other debris in the air, to determine the line-of-sight relative velocity of the air. An inherent limitation of this type of system is its inability to measure velocities perpendicular to the line-of-sight. The presence of a microburst can be detected by measuring the divergence of the horizontal velocity profile, yet, the inability to measure the downdraft can result in a significant underestimate of the magnitude and spatial extent of the hazard.

Wind Shear Hazard Index

The "F-factor"

For straight and level flight

$$F = \frac{\dot{u}}{g} - \frac{w}{V}$$

Related to the potential rate of climb

$$\dot{h}_p = V \left(\frac{T - D}{W} - F \right)$$

The magnitude of the hazard posed by a microburst to an airplane can be expressed in terms of the "F-factor."[†] The F-factor is a nondimensional hazard index that represents the rate of specific energy loss due to wind shear. For straight and level flight the F-factor is a simple function of the rate of change of the horizontal wind, the vertical wind, the acceleration due to gravity, and the airplane's airspeed. Positive values of F indicate a performance-decreasing situation. Conversely, negative values indicate a performance-increasing condition. Doppler-based wind shear sensors can only measure the first term in the F-factor equation, which can result in a significant underestimate of the hazard.

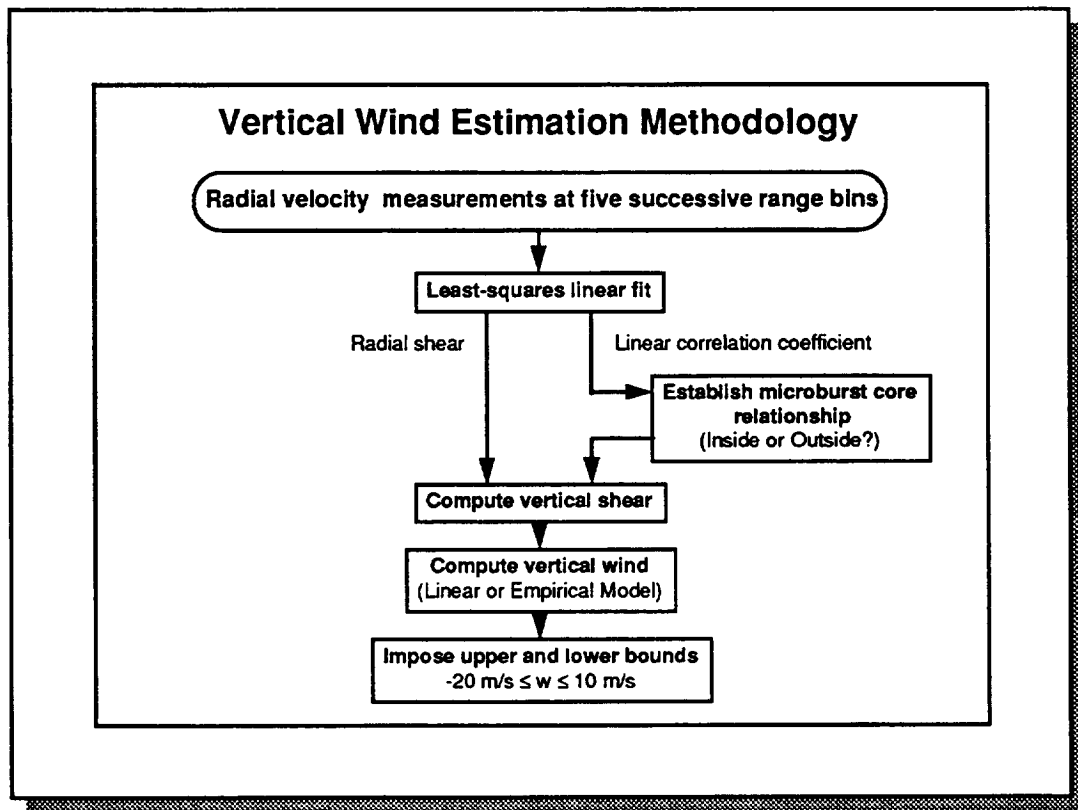
[†] Bowles, Roland L.: *Reducing Wind Shear Risk Through Airborne Systems Technology*. 17th Congress of the International Congress of Aeronautical Sciences, Stockholm, Sweden, September 1990.

Basic Assumptions of Vertical Wind Estimation

- Divergent radial winds (+ shear) produce downdrafts and conversely, convergent radial winds (- shear) produce updrafts.
- Magnitude of the vertical wind is proportional to the magnitude of the shear.

The next several charts will describe the method used to estimate the vertical wind from the radial wind measurements. Two vertical wind models were tested with this method. The models shared two basic assumptions about how the vertical wind varies with the horizontal shear. The first assumption is that divergent radial winds (positive shear) are associated with downdrafts and conversely, convergent radial winds (negative shear) are associated with updrafts. The second assumption is that the magnitude of the vertical wind is proportional to the magnitude of the shear. A previous study[†] established that these two assumptions were reasonable for a simple axisymmetric microburst.

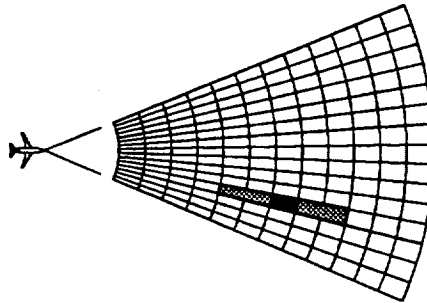
[†] Vicroy, Dan D.: Assessment of Microburst Models for Downdraft Estimation. *Journal of Aircraft*, vol. 29, no. 6, Nov.-Dec. 1992, pp. 1043-1048.



This flow chart shows the vertical wind estimation methodology. The next several charts provide greater detail about the process. A least-squares linear fit of the radial velocity measurements at five successive range bins is used to compute the radial shear and a linear correlation coefficient. The linear correlation coefficient is used to determine whether the measurement is inside or outside the microburst core. This information along with the radial shear is used to compute the vertical shear. The vertical wind is then computed using the linear or empirical vertical wind model. An upper and lower bound is then imposed on the solution.

Computing Radial Shear

- Least-squares linear fit of the radial velocity measurements at five successive range bins



The radial shear at a given range bin is computed using a five point linear least-squares fit. The radial shear is assigned to the middle range bin. The linear correlation coefficient is also computed

Vertical Shear Estimation

- Based on principle of mass continuity
 - Assumes: Symmetrical microburst without rotation
Sensor tilt angle is small

In microburst core

$$\frac{\partial w_m}{\partial z_m} = -2 \frac{\partial u_s}{\partial r_s}$$

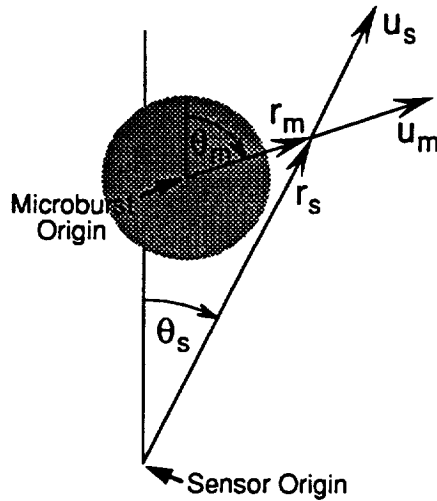
Outside microburst core

$$\frac{\partial w_m}{\partial z_m} = - \frac{\partial u_s}{\partial r_s}$$

- Requires identification of microburst core

The vertical shear was computed from the measured radial shear using the principle of mass conservation, coordinate system transformation equations and some basic assumptions about the microburst and radar geometry. The next two charts outline this derivation.

Radial Shear Transformation Equation (In Microburst Core)



Assuming a symmetrical microburst
with no rotational velocity

$$\frac{\partial u_s}{\partial r_s} = \frac{\partial u_m}{\partial r_m} \cos^2 (\theta_m - \theta_s) + \frac{u_m}{r_m} \sin^2 (\theta_m - \theta_s)$$

In the core of a microburst:

$$\frac{\partial u_m}{\partial r_m} \approx \frac{u_m}{r_m}$$

therefore:

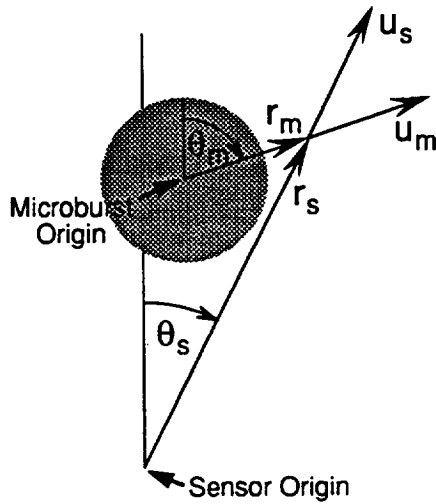
$$\frac{\partial u_s}{\partial r_s} \approx \frac{\partial u_m}{\partial r_m} \approx \frac{u_m}{r_m}$$

or:

$$\frac{\partial u_m}{\partial r_m} + \frac{u_m}{r_m} = -\frac{\partial w}{\partial z} \approx 2 \frac{\partial u_s}{\partial r_s}$$

This chart shows the radial shear transformation equation from a microburst-centered coordinate system to a sensor-referenced coordinate system under some simplifying assumptions. If the radial shear is assumed to be linear in the microburst core, then the transformation equation becomes a simple equality. If this equality is then applied to the mass conservation equation, a simple equation for the vertical velocity gradient as a function of the sensor measured radial shear is obtained.

Radial Shear Transformation Equation (Outside Microburst Core)



Assuming a symmetrical microburst
with no rotational velocity

$$\frac{\partial u_s}{\partial r_s} = \frac{\partial u_m}{\partial r_m} \cos^2 (\theta_m - \theta_s) + \frac{u_m}{r_m} \sin^2 (\theta_m - \theta_s)$$

Outside microburst core:

$$\frac{u_m}{r_m} \rightarrow 0 \text{ as } r_m \rightarrow \infty$$

$$\text{therefore: } \frac{\partial u_s}{\partial r_s} \approx \frac{\partial u_m}{\partial r_m} \cos^2 (\theta_m - \theta_s)$$

$$\text{or: } \frac{\partial u_s}{\partial r_s} \geq \frac{\partial u_m}{\partial r_m}$$

For large

$$\frac{\partial u_m}{\partial r_m} + \frac{u_m}{r_m} = -\frac{\partial w}{\partial z} \approx \frac{\partial u_m}{\partial r_m} \leq \frac{\partial u_s}{\partial r_s}$$

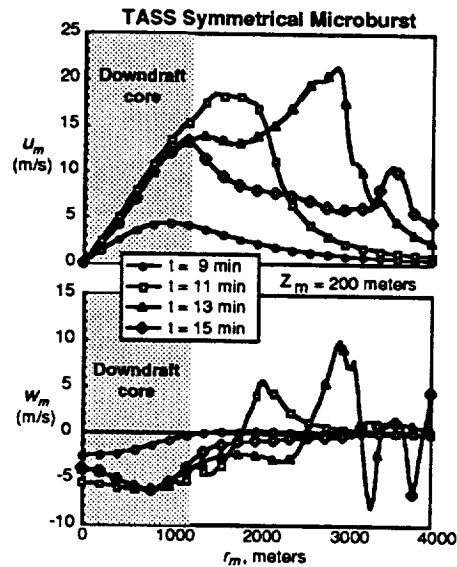
This chart uses the same transformation equation as the previous chart but assumes that the measurements are made outside the microburst core. As the distance from the microburst core increases, simplifying assumptions can be made which result in an inequality relationship between the vertical wind gradient and the sensor measured radial wind.

Microburst Core Criteria

- Near the downdraft core the radial velocity variation is nearly linear
- Linear correlation coefficient used to distinguish core

$R \geq 0.9$ inside microburst core

$R < 0.9$ outside microburst core



The location of the measurement relative to the microburst core must be established to accurately estimate the vertical shear, which is then used to compute the vertical wind. The microburst core criteria was established from observations of the characteristics of axisymmetric microburst models. Near the downdraft core the radial velocity variation is nearly linear. From this observation it was established that if the radial shear was positive with a linear correlation coefficient of 0.9 or greater, then the measurement was assumed to be in the microburst core. Otherwise the measurement was assumed to be outside the microburst core.

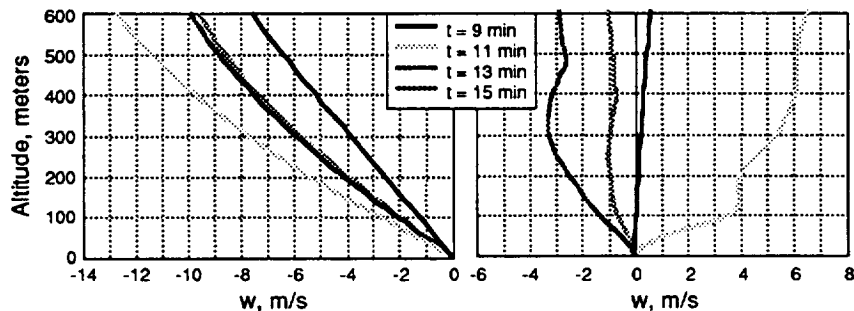
Linear Model

- Assumes the vertical wind is zero at the ground and varies linearly with altitude

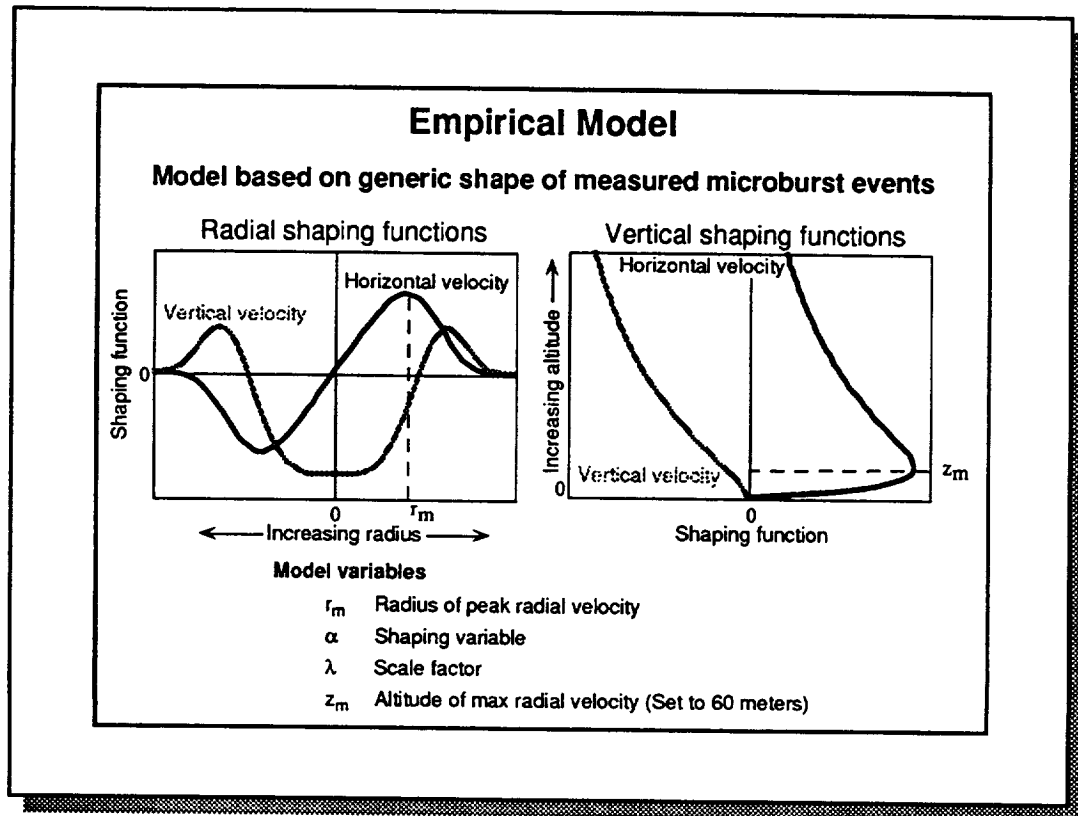
$$w_m = \frac{\partial w_m}{\partial z_m} z_m$$

Downdraft is linear near core

Nonlinear near outflow vortex



With the estimate of the vertical divergence in hand, the next step was to develop models for computing the vertical wind from the vertical divergence. Two models were developed. The simplest was the "linear model." If the vertical wind is assumed to be zero at the ground and vary linearly with altitude, then the vertical wind can be expressed as a simple function of the radial velocity profile. The linear assumption appears reasonable in or near the core of the microburst but poor near the outflow vortex.



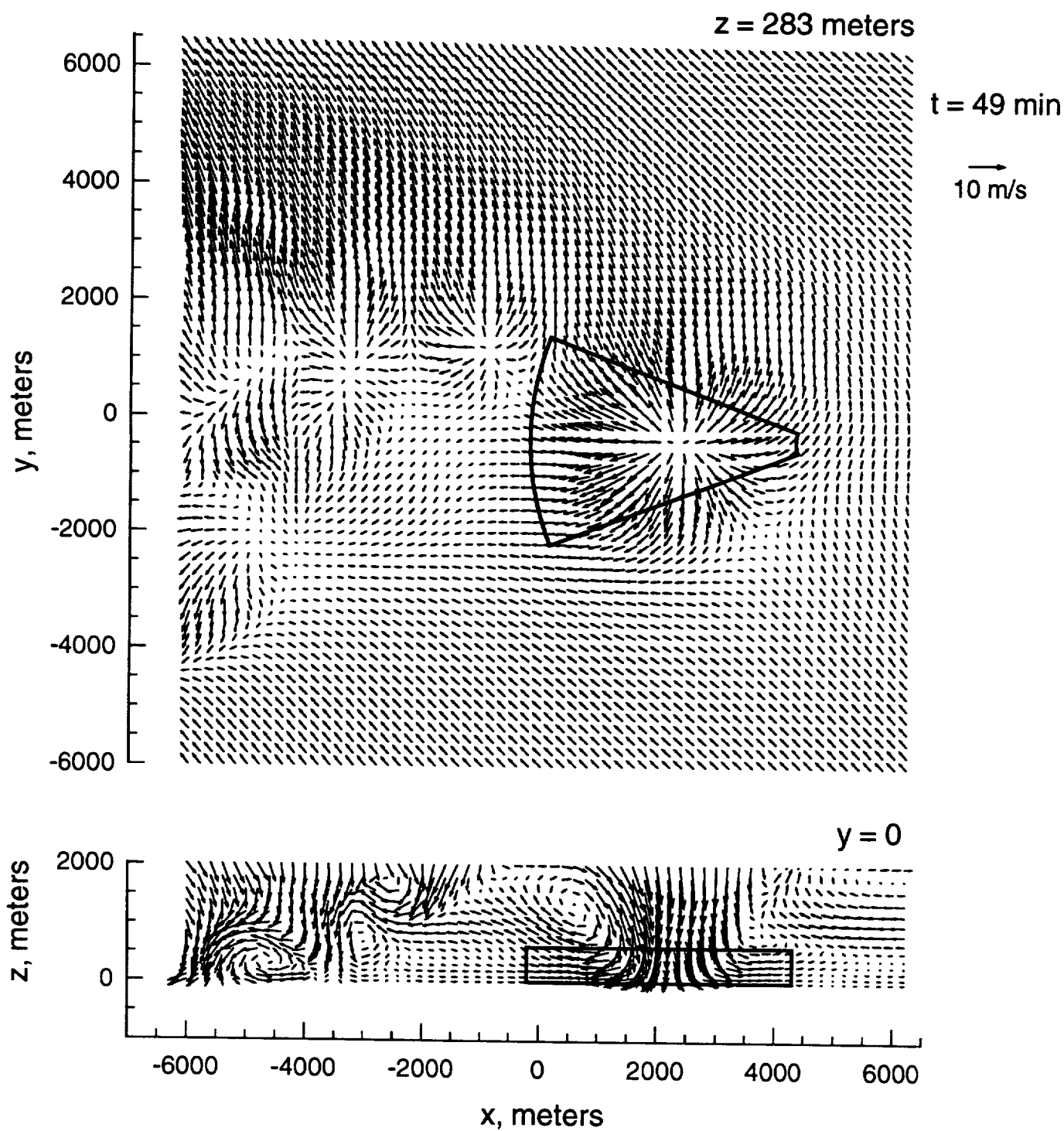
As the name implies, this model is based on measurements of several microburst events. The empirical model is an axisymmetric steady-state model that uses shaping functions to satisfy the mass continuity equation and simulate boundary layer effects.[†] The shaping functions are used to approximate the characteristic profile of the microburst winds. The empirical model is fully defined through four model variables: the radius and altitude of the maximum horizontal wind, a shaping variable, and a scale factor.

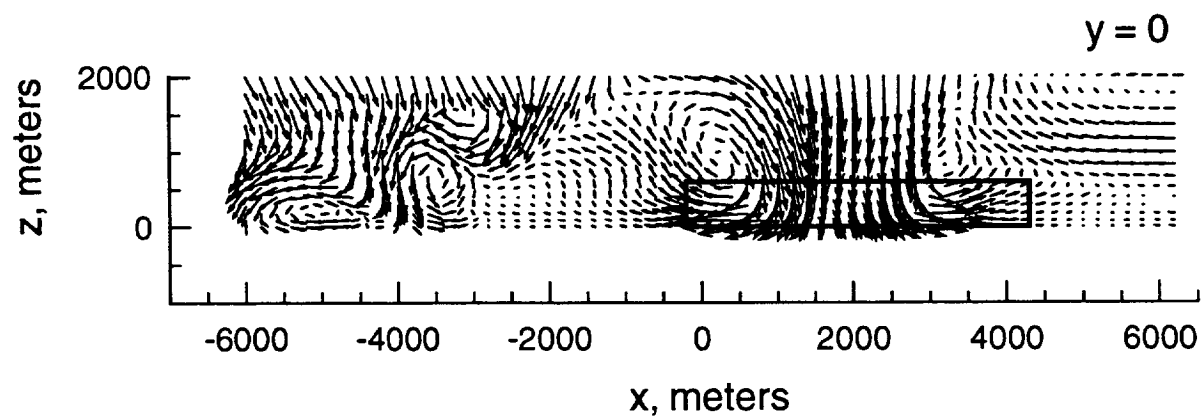
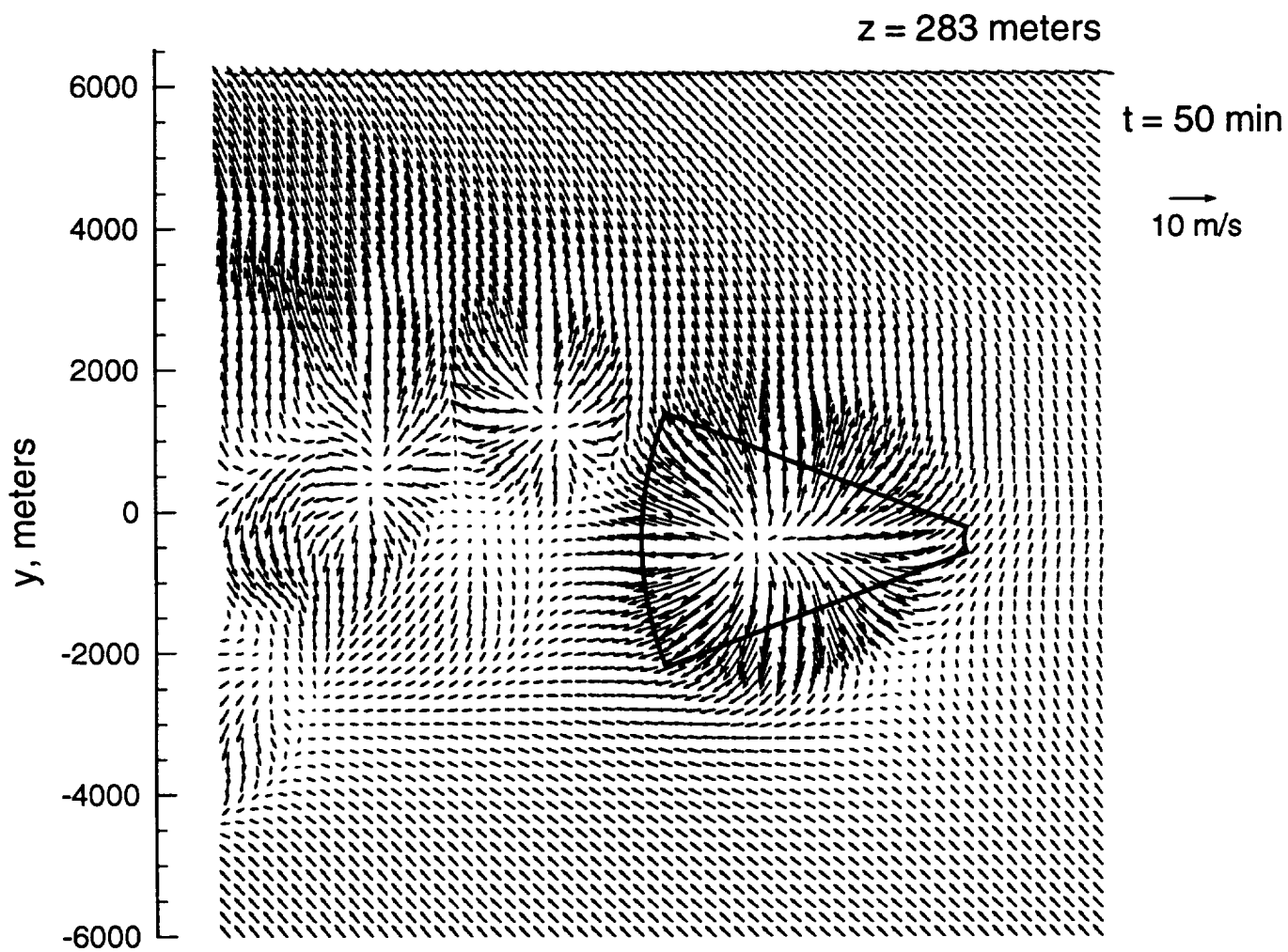
[†] Vicroy, Dan D.: *A Simple, Analytical, Axisymmetric Microburst Model for Downdraft Estimation*. NASA TM-104053, DOT/FAA/RD-91/10, February 1991.

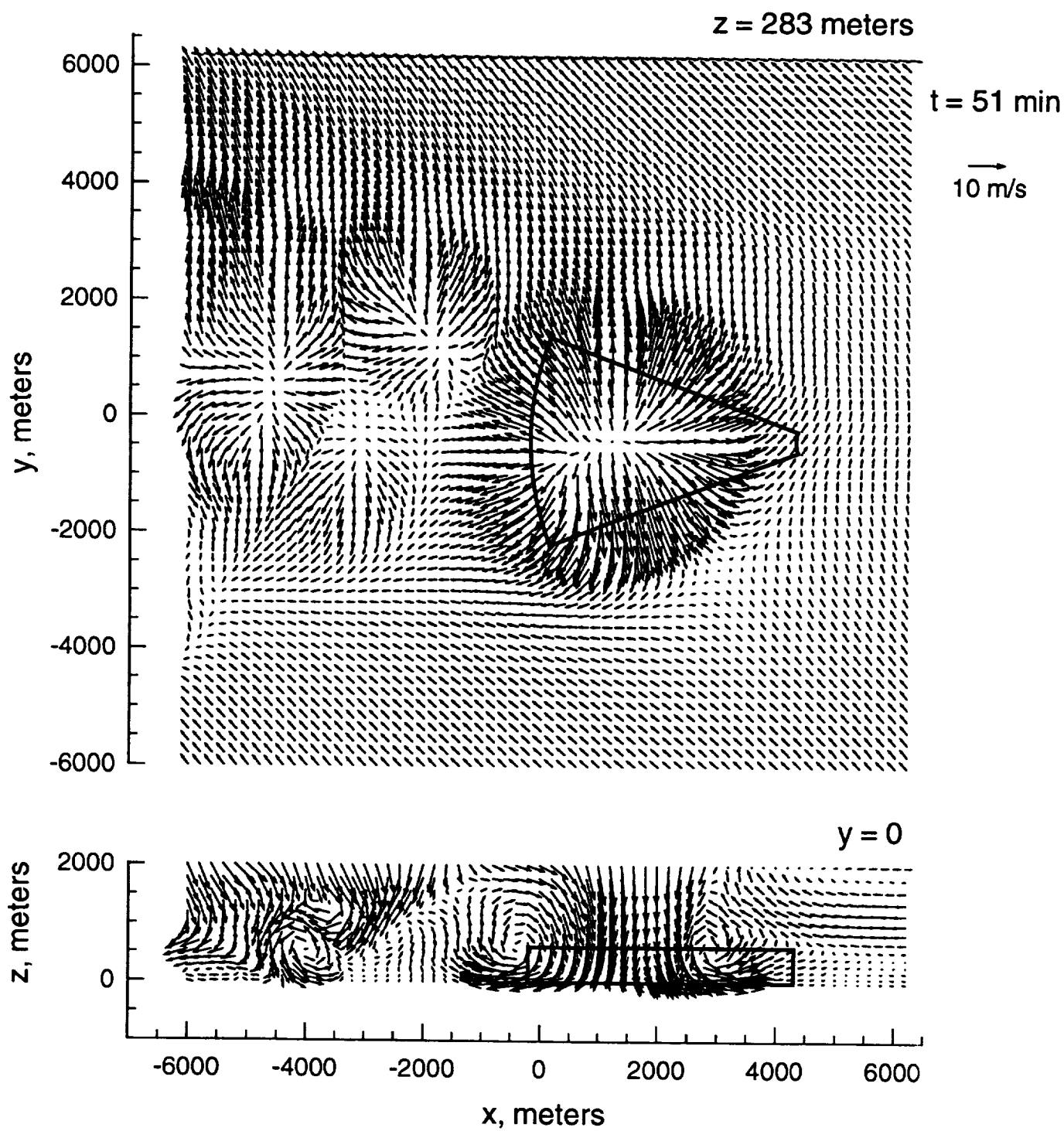
Simulation Study

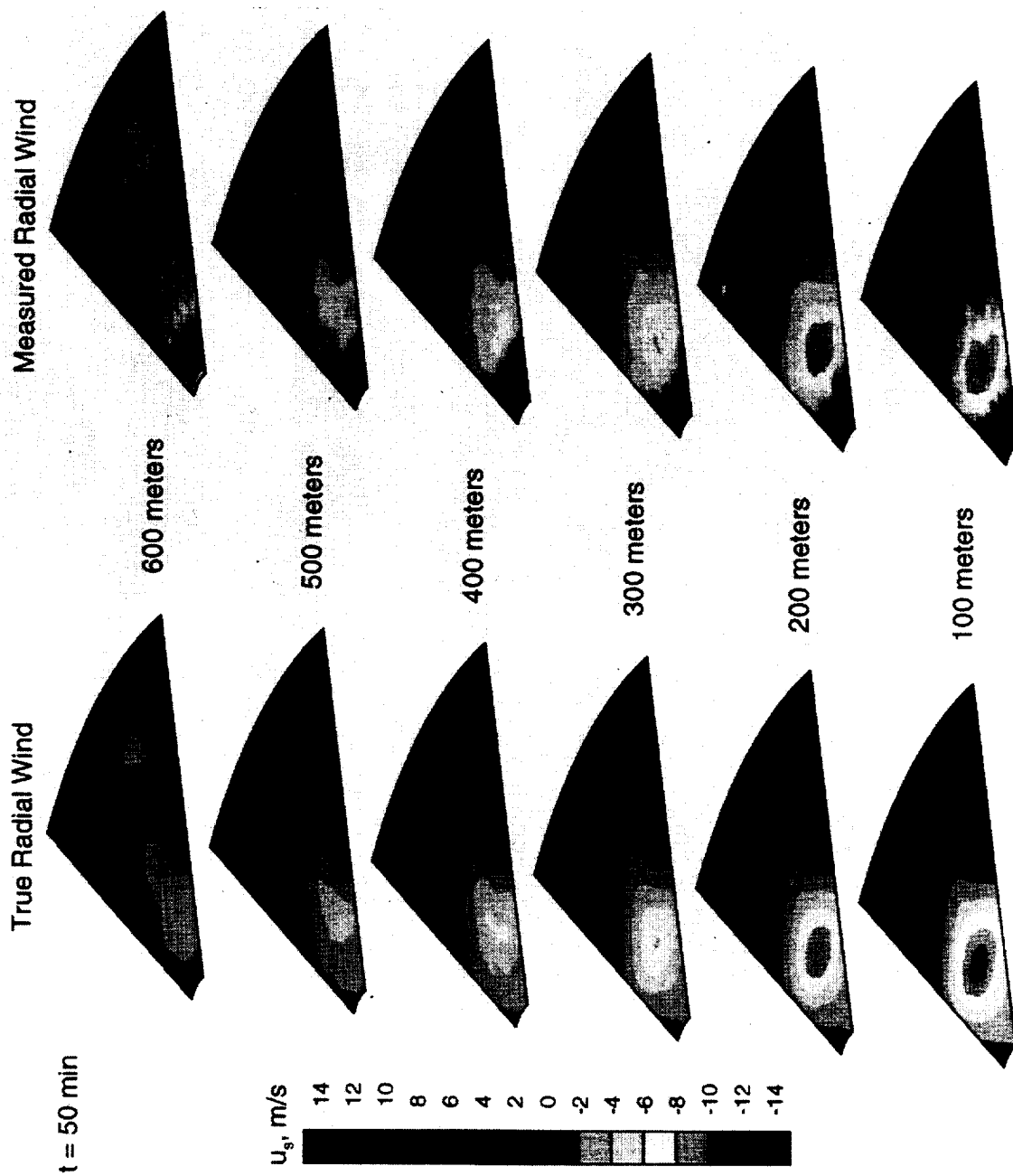
- Airborne Windshear Doppler Radar Simulation (AWDRS)
 - Included effects of ground clutter and signal noise
 - Scan azimuth was ± 21 deg. in 3 deg. increments
 - 30 range bins, 150 m long, initial range 425 m
- 3 TASS generated asymmetric microburst data sets of the July 11, 1988 Denver microburst
 - The data set times corresponded to approximately 1 min prior, during and 1 min after the first airline encounter
- Radar scans at altitudes of 100 to 600 m in 100 m increments
 - Zero antenna tilt for all but 100 and 200 m scans (1.2 and 0.5 deg., respectively)

A Doppler radar simulation was used in conjunction with a high fidelity asymmetric microburst model to establish the performance limits of the vertical wind models and establish the effects of radar signal noise and measurement errors. Detailed results of this study and the subsequent flight test will be available in a NASA Technical Paper entitled *"Microburst Vertical Wind Estimation from Horizontal Wind Measurements,"* which will be published Spring 1994. The next three charts show the wind vector field and the radar scan area of the microburst data sets used in the radar simulation.

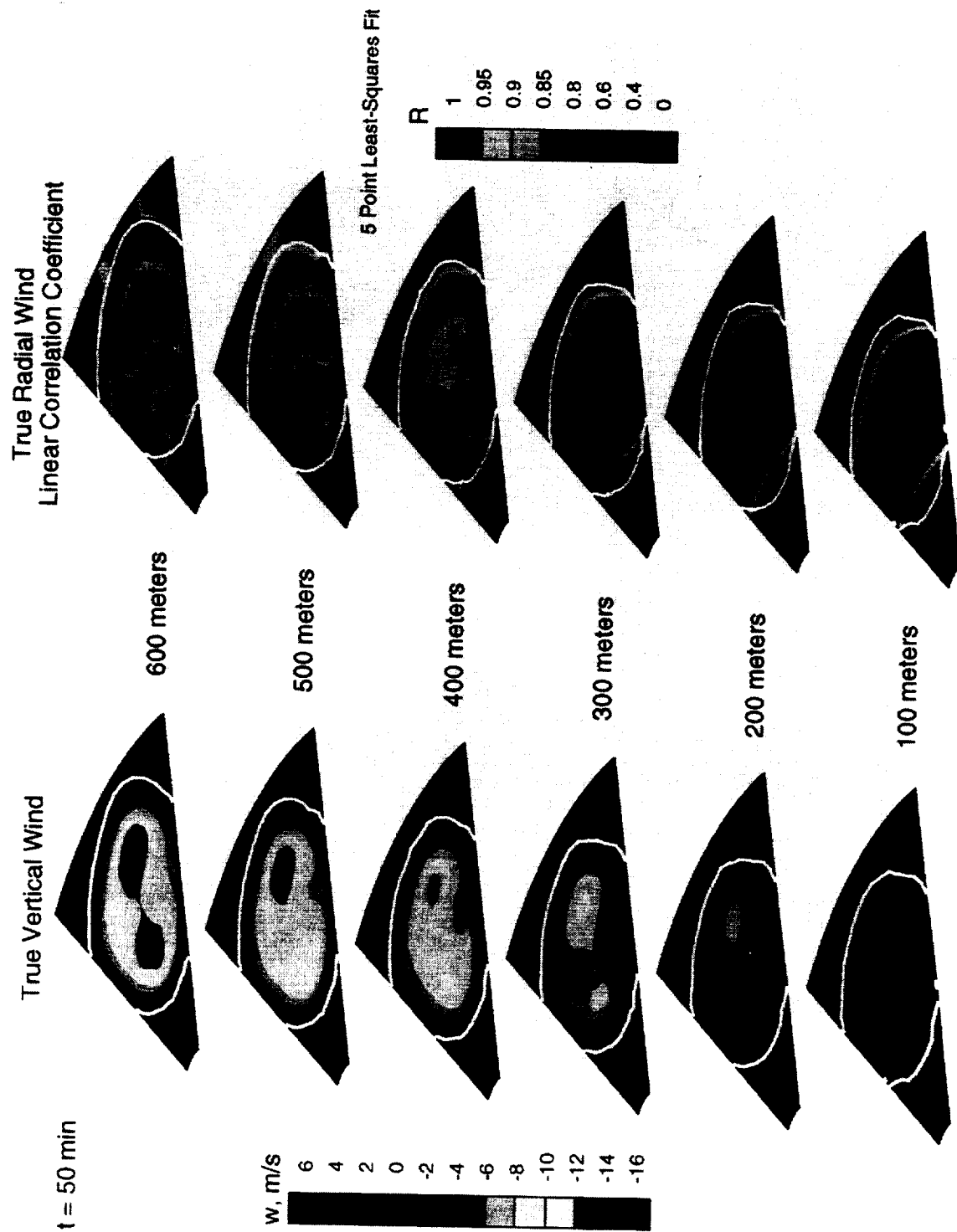




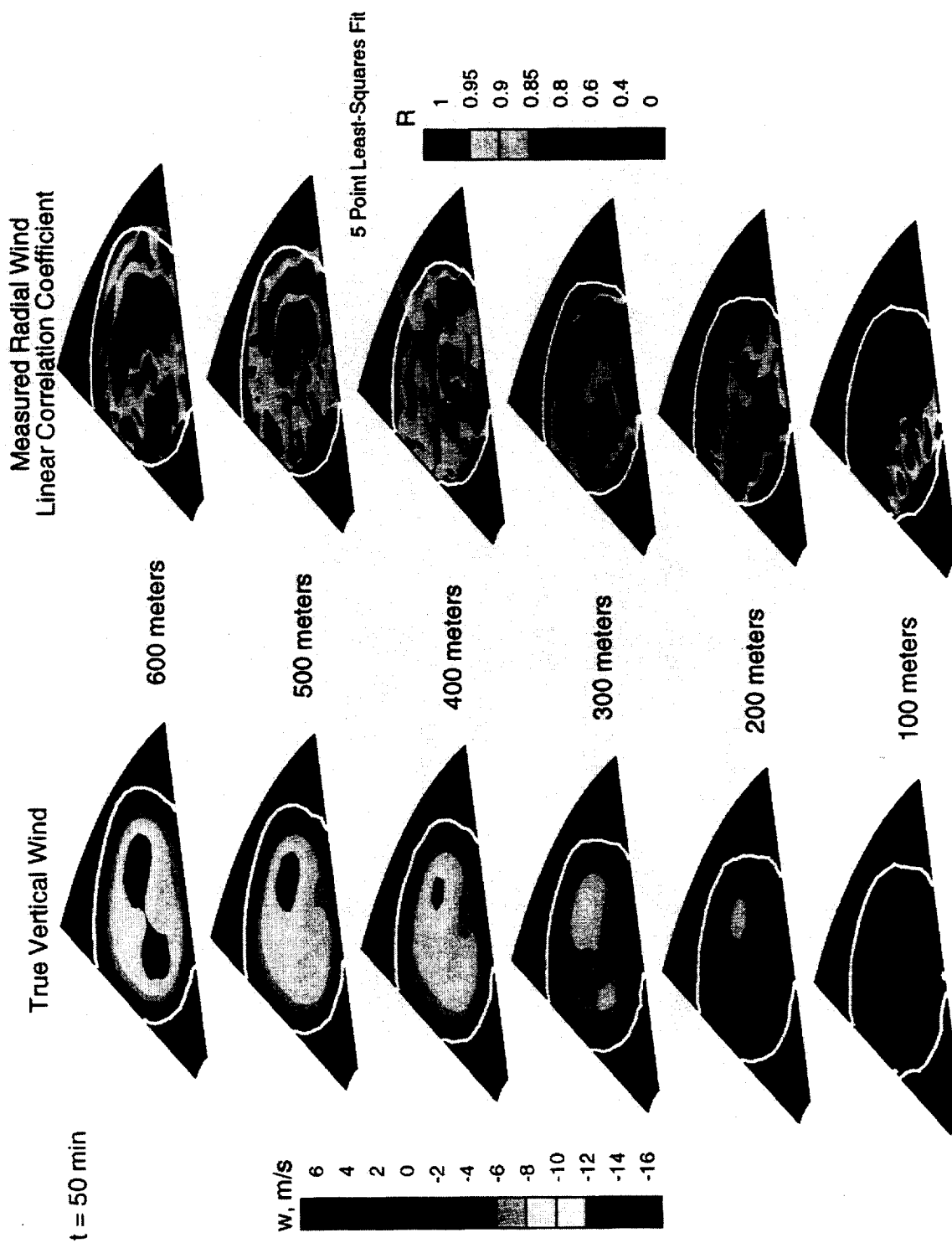


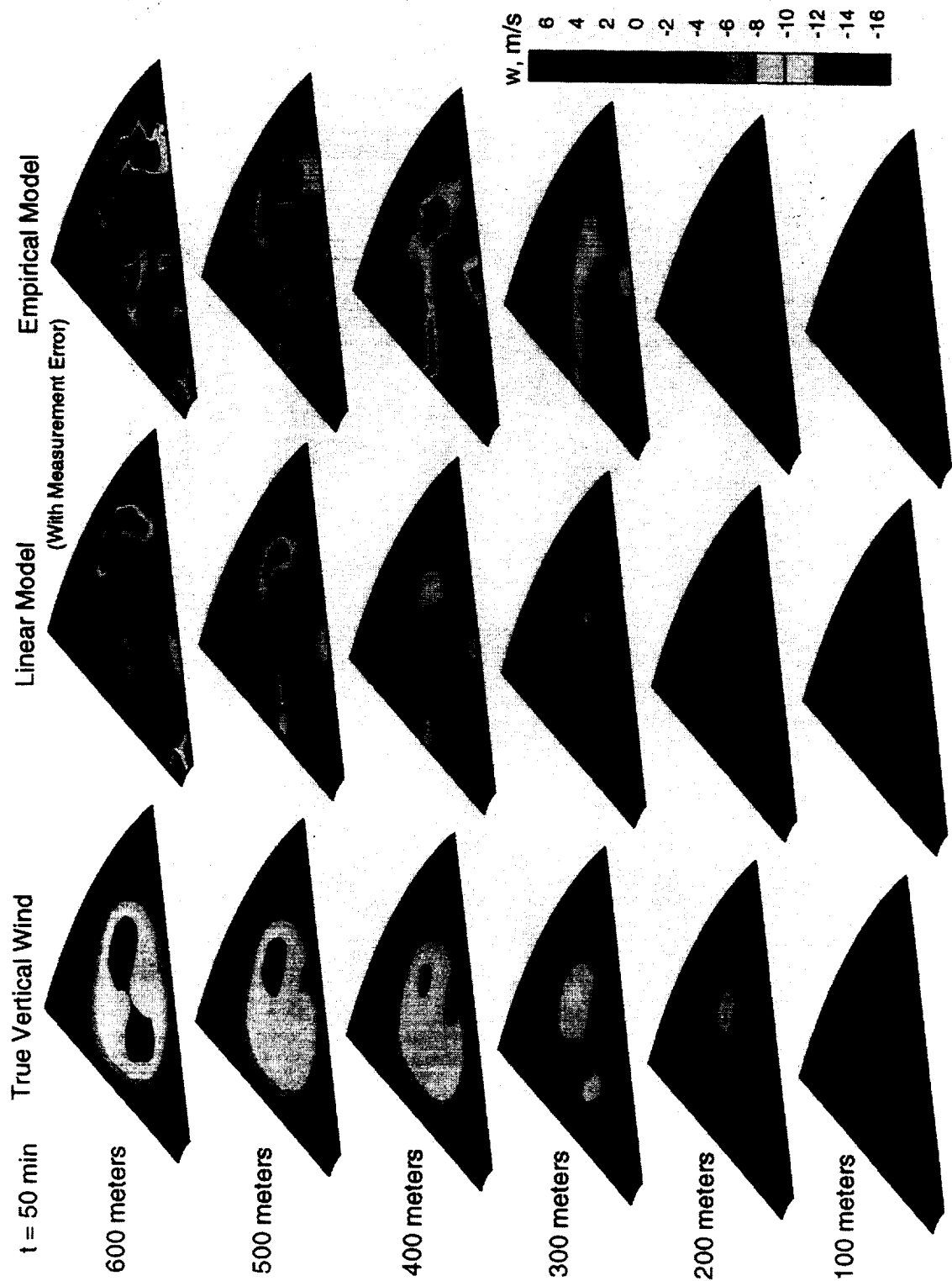


This chart shows the effect of signal noise and ground clutter in the measured radial wind at six different scan altitudes for one of the microburst data sets.



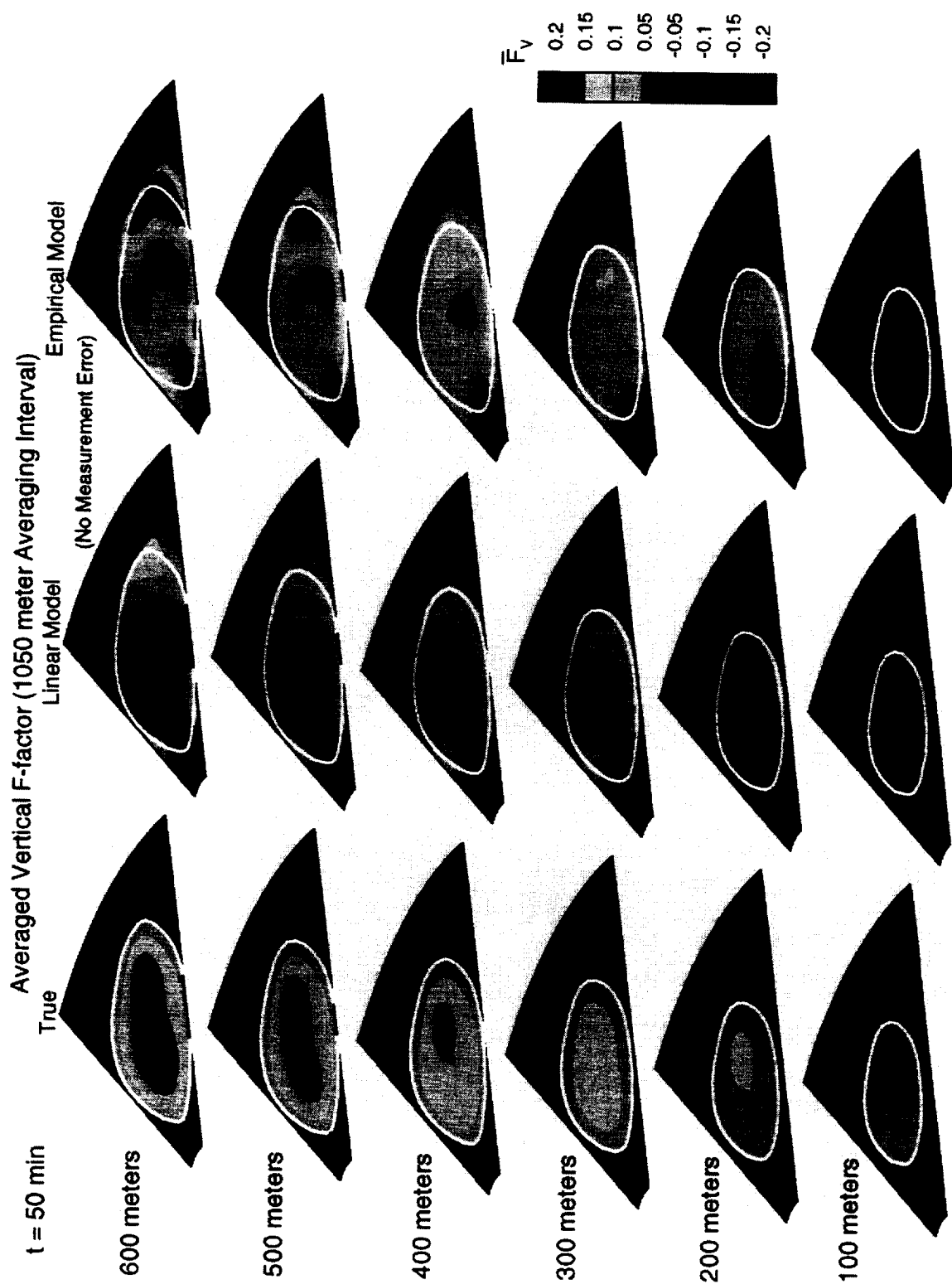
The next two charts illustrate the validity of the microburst core criteria and the effect of radar measurement error. The white contour line marks the downdraft portion of the microburst.

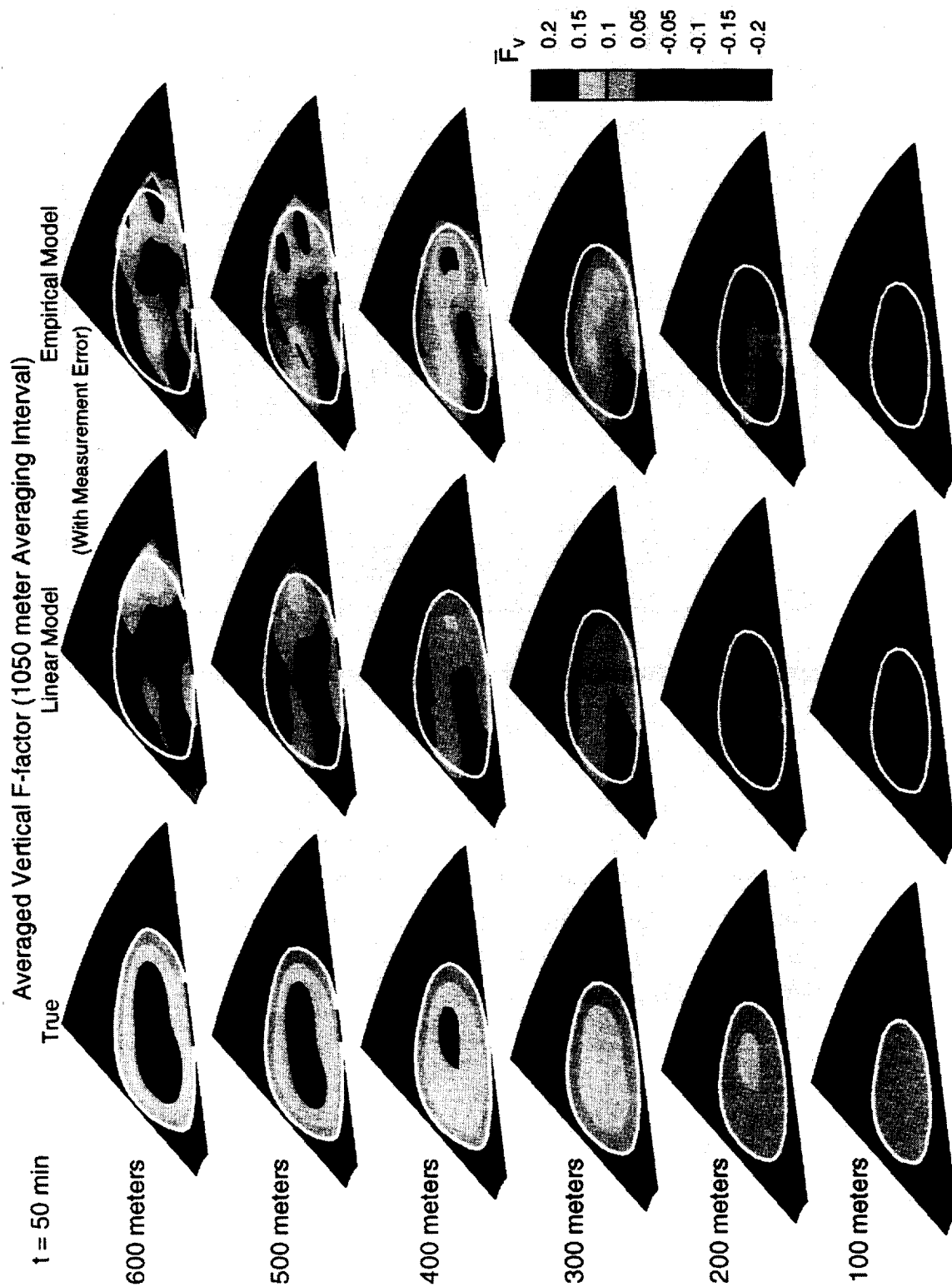


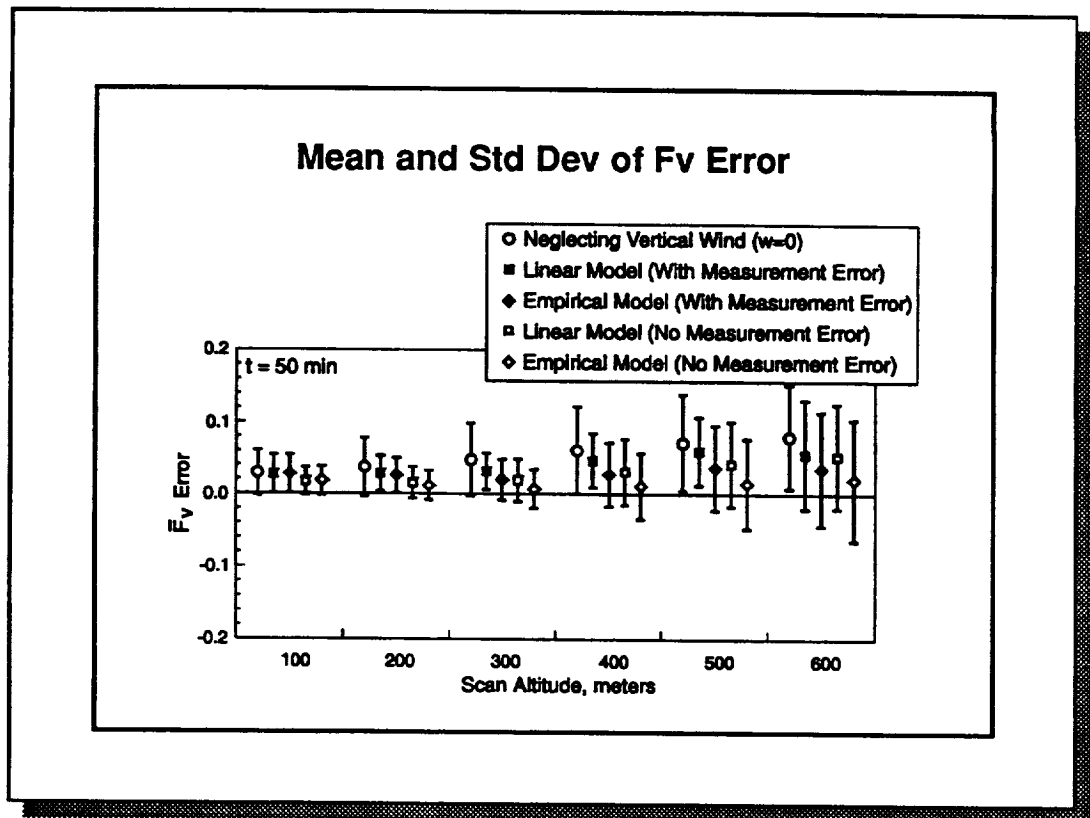


This chart show the true and the estimated vertical wind from the two models with the radar measurement error effects.

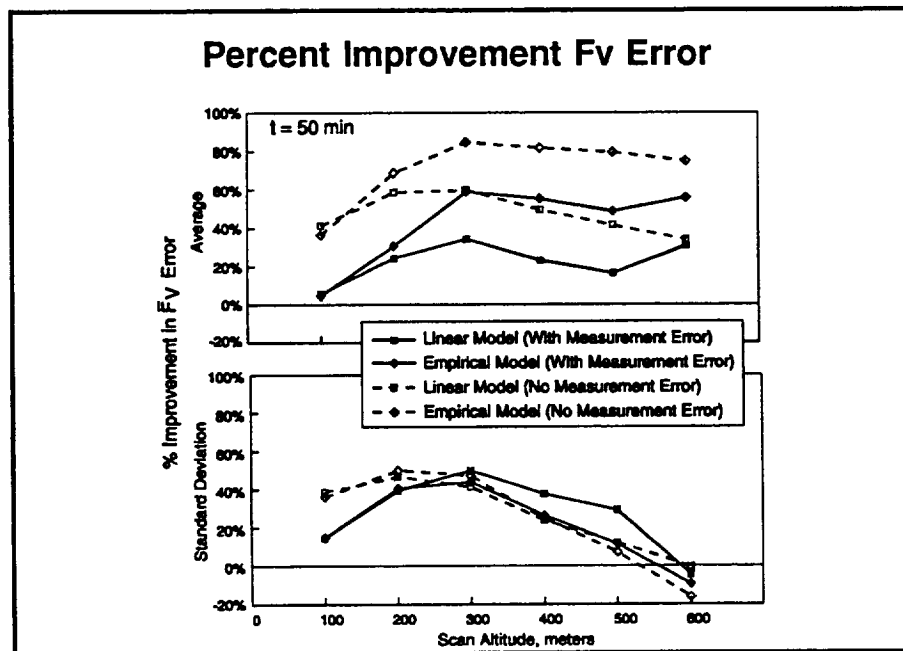
The next two charts show the true and the estimated averaged vertical F-factor, with and without radar measurement errors, respectively. Estimating the vertical component of hazard factor is the end goal of the vertical wind estimation algorithm. The true 0.05 vertical F-factor contour is highlighted in white to distinguish the area where the vertical contribution is at least half of the hazard alert threshold.







The mean and standard deviation of the vertical F-factor error are shown in this chart for each scan altitude. The errors tend to increase with altitude. At the altitudes of primary interest for wind shear detection, at or below 300 meters, the mean error (for all three microburst data sets) was between 0.010 and 0.042 with the standard deviation between 0.014 and 0.028.

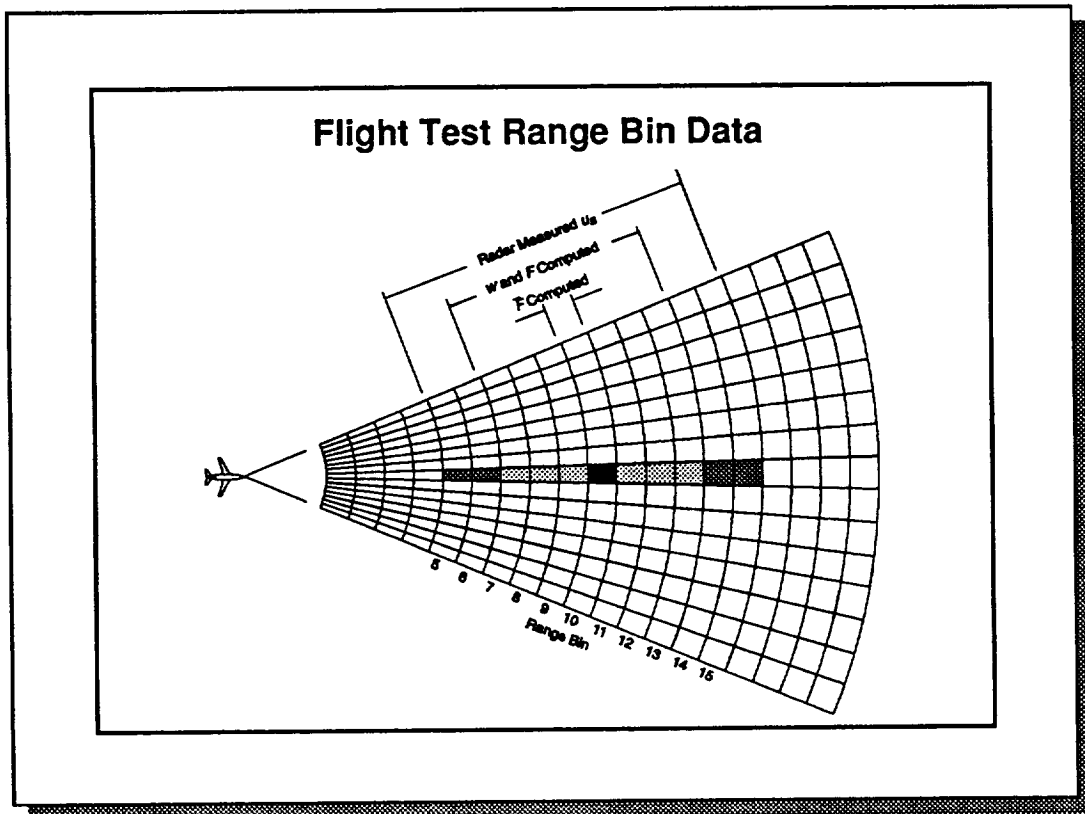


This chart show the percent improvement in the mean vertical F-factor error. The altitude of maximum performance improvement of the models occurs at about 300 meters. Above 300 meters the percent improvement diminishes due to increased modeling error. Below 300 meters the percent improvement is minimized by the diminished magnitude of the vertical wind.

Flight Test

- Onboard in situ measurement used as "truth"
- In situ measurement compared with radar derived estimate at the 2 km range gate (range bin 10 along 0 azimuth)
- 10 microburst or gust front events selected for evaluation
 - Selection criteria: Flight path was nearly straight and level
Zero antenna tilt
0.96 μ sec pulse width

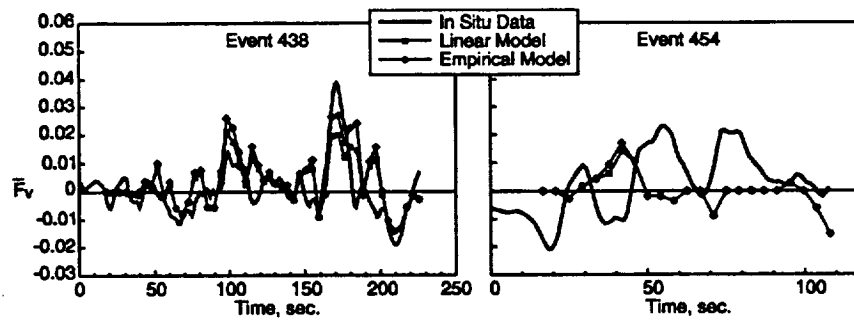
A series of flight tests were conducted during the summers of 1991 and 1992 with NASA's Boeing 737-100 test airplane equipped with a variety of prototype wind shear detection systems. The airplane's reactive, or in situ, system computed the F-factor of the airspace the airplane was currently flying through. This in situ measurement was used as a "truth" measurement for validation of the forward-look wind shear detection sensors. The F-factor predicted from the forward-look sensor was compared with the airplane's in situ measurement as it penetrated the scanned airspace.



This chart illustrates the radar range bin measurements required to compute a one-kilometer-averaged F-factor at a range gate 2 kilometers in front of the airplane.

The next two charts show sample comparisons of the averaged vertical F-factor from the in situ measurement and the radar estimate at the 2 kilometer range gate. The time scale for the radar measurement was shifted by the time required for the airplane to reach the radar measured location.

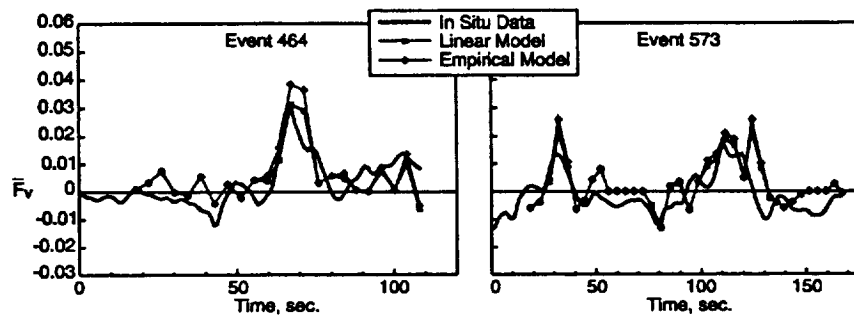
Sample Flight Test Results

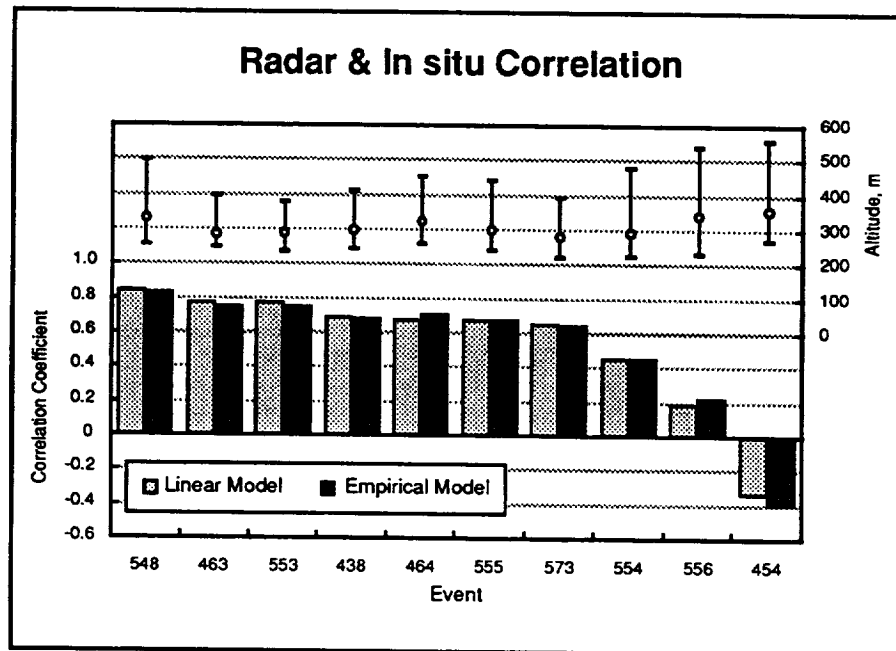


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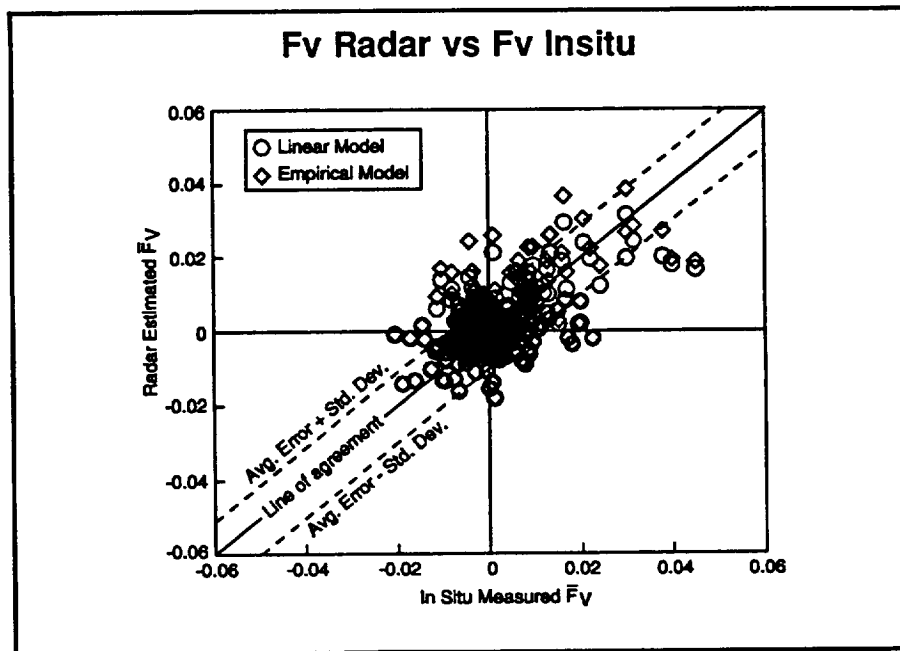
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Sample Flight Test Results





This chart shows a summary of the correlation between the in situ and the radar estimate, plotted from best to worst. Also shown on the figure is the maximum, minimum and average altitude during the event. In general, the events with the largest altitude variation through the run also had the poorest correlation, indicating that perhaps the airmass measured by the radar was not the same as the in situ measured airmass. However, this hypothesis is not conclusive in that the event that yielded the best correlation also had a large altitude deviation.



This chart shows a composite comparison of the estimated average vertical F-factor and the in situ measured. Also shown in the figure is the line of perfect agreement and the lines of plus and minus one standard deviation about the average error. The average error for the linear and empirical models was 0.0001 and -0.0007, with standard deviations of 0.0087 and 0.0093, respectively. The standard deviation lines shown on the figure are the maximum of the two.

Concluding Remarks

- Results from the simulation and flight test showed that the linear and empirical vertical wind models both improved the hazard estimate
- The performance difference between the two models was insignificant
- The altitude of maximum benefit was about 300 meters. (less vertical wind at lower altitudes and more error at higher altitudes)
- Vertical hazard estimate is sensitive to velocity measurement errors
- Flight test results were better than predicted by simulation study

The objective of this study was to assess the ability of simple vertical wind models to improve the hazard prediction capability of an airborne Doppler sensor in a realistic microburst environment. The results indicate that in the altitude region of interest (at or below 300 meters), both the linear and empirical vertical wind models improved the hazard estimate. The radar simulation study showed that the magnitude of the performance improvement was altitude dependent. The altitude of maximum performance improvement occurred at about 300 meters. At the lower altitudes the percent improvement was minimized by the diminished contribution of the vertical wind. The vertical hazard estimate errors from flight tests were less than those of the radar simulation study.